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Physical exercise and cognitive function across the life span: results of a nationwide population-based study

Authors: Beate Gaertner, PhD[a]; Amanda K Buttery, PhD[a,b]; Jonas D Finger, PhD[a]; Steffen Wolfsgruber, PhD[c,d]; Michael Wagner, PhD [c,d]; Markus A Busch, MD[a]

[a]Department of Epidemiology and Health Monitoring, Robert Koch Institute Berlin, Germany;

[b]King's College London, Faculty of Life Sciences and Medicine, London, United Kingdom;

[c]Department of Psychiatry and Psychotherapy, University of Bonn, Germany;

[d]German Center for Neurodegenerative Diseases (DZNE), Bonn, Germany

Corresponding Author: Dr. Beate Gaertner, Department of Epidemiology and Health Monitoring, Robert-Koch-Institute, General-Pape-Str. 62-66, D-12101 Berlin, Germany; Phone: +49-30-18745-3745, Fax: +49-30-18745-3211; GaertnerB@rki.de

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ABSTRACT

Objectives: To examine cross-sectional and longitudinal associations between physical exercise and cognitive function across different age groups in a nationwide population-based sample of adults aged 18 to 79 years in Germany.

Design: Cross-sectional/Prospective.

Methods: Cognitive function was assessed in the mental health module of the German Health Interview and Examination Survey for Adults (DEGS1-MH, 2009-2012, n=3535), using a comprehensive neuropsychological test battery. Cognitive domain scores for executive function and memory were derived from confirmatory factor analysis. Regular physical exercise in the last three months was assessed by self-report and defined as no exercise, <2 and ≥2 hours (h) of exercise per week. A subgroup of DEGS1-MH participants who previously participated in the German National Health Interview and Examination Survey 1998 (GNHIES98, 1997-1999, n=1624) enabled longitudinal analyses with a mean follow-up of 12.4 years.

Results: Compared to no exercise, more weekly physical exercise was associated with better executive function in cross-sectional (<2h: ß=0.12; ≥2h: ß=0.17; all p<0.001) and longitudinal analyses (<2h: ß=0.14, p<0.001; ≥2h: ß=0.15, p=0.001) using linear regression models adjusted for age, sex, education, smoking, alcohol consumption, fruit and vegetable consumption and obesity. Slightly weaker associations were found for memory in cross-sectional (<2h: ß=0.08, p=0.009; ≥2h: ß=0.08, p=0.026) and longitudinal analysis (<2h: ß=0.09, p=0.036; ≥2h: ß=0.08, p=0.114). There was no evidence of interaction between physical exercise and age.

Conclusions: Higher levels of physical exercise were associated with better executive function and memory in cross-sectional and longitudinal analyses with no evidence for differential effects by age.

Keywords: memory; executive function; risk factors; longitudinal studies; neuropsychological assessment; health examination survey

1. Introduction

Cognitive impairment is a rising concern among ageing populations across the world.[1,2] Global public health policy is increasingly focusing attention on prevention strategies to minimize the risks of developing cognitive impairment, especially given the lack of currently available curative therapy for dementia.[1,3] Increasing physical activity levels have been central to public health strategies for the prevention of cardiovascular disease for decades. Growingly, physical activity is regarded as an important prevention target for dementia and cognitive decline.

Studies examining the relationships between physical activity and cognition have focused mainly on older adults and the development of impaired cognitive function. Results from prospective studies, including meta-analyses, indicate positive effects of physical activity on cognitive function,[4] dementia risk and cognitive decline.[5] However, there is less evidence available for young or middle-aged adults, despite this being a potentially important target period for maintaining brain health. A recent systematic review for this age-group (18–50 years) reported positive associations between physical activity and cognitive function in studies with mostly small, non-population based, cross-sectional samples.[6] Longitudinal studies in this age group have reported mixed results on associations of physical activity with cognitive function.[7-9] Therefore, studies with large longitudinal population-based samples are needed to examine the differential effects of physical activity on cognitive function across the lifespan.

In a large, nationwide population-based sample of cognitively healthy adults aged 18 to 79 years in Germany we examine relationships between physical exercise and cognitive function across the life span. The aim of this study is: (1) to examine cross-sectional and longitudinal associations between physical exercise and cognitive function in two main cognitive domains (executive function and memory) and, (2) to examine whether these associations differ across the age span.

2. Methods

2.1 Study design and sample

The design of the nationwide population-based German Health Interview and Examination Survey for Adults (DEGS1, November 2008 – November 2011) and its mental health module (DEGS1-MH, September 2009 – March 2012) have been described in detail elsewhere.[10,11] In brief, DEGS1 combines a longitudinal sample of individuals who have previously participated in the nationwide population-based German National Health Interview and Examination Survey 1998 (GNHIES98, October 1997 – March 1999)[12,13] and a new cross-sectional sample also derived by a two-stage random sampling procedure of communities and local population registers.[11] The aim of these surveys is to obtain comprehensive information about the health of the community-living population aged 18-79 years in Germany and monitor both physical and mental health.

DEGS1 was approved by the federal and state commissioners for data protection and by the ethics committee of Charité-Universitätsmedizin Berlin (No. EA2/047/08). DEGS1-MH was additionally approved by the ethics committee of the Technische Universität Dresden (No. EK174062009). GNHIES98 was approved by the federal office for data protection. Written informed consent was provided by all participants prior to the interviews.

Data was collected by self-administered written questionnaires, standardised physician-administered computer-assisted personal interviews (CAPI), and a range of physical, laboratory and other measurements in DEGS1 and GNHIES98. Standardised computer-assisted Composite International Diagnostic Interview (CIDI), a detailed neuropsychological test battery, and self-administered questionnaires were used in DEGS1-MH.

There were 7124 participants in the GNHIES98 and the survey had an overall response rate of 61%.[13] DEGS1 response rates were 64% for previous GNHIES98 participants and 42% for the newly sampled participants.[11] Of 7987 DEGS1 participants aged 18-79 years, 4483 individuals also participated in DEGS1-MH.[10] The median time lag between DEGS1 and DEGS1-MH was 6 weeks (interquartile range: 5-25 weeks).

For the present cross-sectional analyses, the following exclusion criteria were consecutively applied to the DEGS1-MH sample (n=4483): neuropsychological test battery not completed (n=94); neuropsychological test battery completed by telephone (n=483); first language not German (n=237); deafness (n=1); profound learning difficulties (n=1); or due to missing data in cognitive domain scores (n=24), physical exercise (n=46) or any covariable (n=62). Therefore, a total of 3535 DEGS1-MH participants were included in these cross-sectional analyses.

For the longitudinal analyses, 1666 of 3643 DEGS1-MH participants with valid data in cognitive domain scores had previously participated in GNHIES98 and were eligible for longitudinal analyses. Of these, 42 participants were excluded because of missing data in GNHIES98 variables (i.e. physical exercise (n=19) or any covariables (n=23)). Thus, 1624 participants were included in the longitudinal analysis. Mean follow-up time was 12.4 years (range, 10.5 to 14.4 years).

2.2 Assessment of cognitive function

Cognitive function was assessed in DEGS1-MH by a comprehensive neuropsychological test battery[10] comprising the digit span backward test (DSBT) from the Wechsler Intelligence Scale for Adults,[14] the trail making tests (TMT-A, TMT-B),[15] the letter digit substitution test (LDST),[16] a verbal fluency test (VFT) from The Consortium to Establish a Registry for Alzheimer's Disease (CERAD),[17,18] and immediate (Trial 1-3) and delayed (Trial 4) recall of a 10-word list from CERAD (see Supplementary material Table A.1 for details on measurement).[17,18] All test scores were z-standardized. To permit comparable interpretation of all tests, the direction of TMT-A and TMT-B z-scores were reversed. Thus, larger z-scores indicate better performance for all tests.

Cognitive domain scores for executive function and memory were derived from confirmatory factor analysis in the form of latent factor scores, if at least three tests for executive function (DSBT, TMT-A, TMT-B, LDST, VFT) and memory (immediate and delayed recall) were available.[19] A two-factor solution with inter-correlated factors provided an excellent fit to the data, significantly outperforming a one-factor solution which yielded insufficient fit to the data. Loadings of the neuropsychological test scores on executive function ranged between 0.480 (DSBT) and 0.835 (LDST); and loadings on memory ranged between 0.705 (Trial 1 immediate recall) and 0.861 (Trial 4 delayed recall). Variance and mean of derived factor scores were fixed to one and zero, respectively, similar to a z-score. Higher values of cognitive domain scores represent better cognitive function.

2.3 Assessment of physical exercise

In both surveys, regular physical exercise in hours (h) per week in the last three months was assessed by self-administered written questionnaire with the following question: “How often do you engage in physical exercise?”[20] The five response categories referred to one week: “not at all”, “less than 1h”, “regularly 1–2h”, “regularly 2-4h”, and “regularly more than 4h”. To receive sufficient cell sizes for analyses, scores were categorized as 0h/week (no exercise), <2h/week or ≥2h/week. The cut-off of ≥2h per week was chosen because this cut-off-point comes closest to the 150 minutes moderate-intensity physical activity per week recommendation.[21]

2.4 Other measures

Other measures were assessed comparably in DEGS1 and GNHIES98. Information on age and sex was obtained from local population registers. Level of education (low, medium, high) was measured according to the Comparative Analysis of Social Mobility in Industrial Nations

(CASMIN) classification,[22] based on self-reported information on school, academic and professional qualifications.

Behavioral risk factors were assessed by self-administered questionnaires and included: current smoking (yes/no), alcohol consumption 0g/d; ≤10/20 g/d women/men; >10/20 g/d women/men; [23] and the intake of fruit and vegetables in the last four weeks (<3 or ≥3 portions per day) according to a Food Frequency Questionnaire.[24] Obesity (yes/no) was defined as a body mass index of ≥30 kg/m² based on standardized measurements of body weight and height.

2.5 Statistical analysis

Cross-sectional associations between physical exercise categories and cognitive domain scores (executive function and memory) were examined by unadjusted and adjusted linear regression analyses. Several a priori defined sociodemographic (age, sex, level of education) and lifestyle factors (smoking, alcohol consumption, fruit and vegetable consumption, obesity) which are known to be associated with physical activity[25] and cognitive function[26] were taken into account as potential confounding factors and were included in adjusted models. Regression models were adjusted in three steps: (1) for age (mean centered and squared) and sex, (2) additionally for level of education and (3) additionally for behavioural risk factors (smoking, alcohol consumption, fruit and vegetable consumption, obesity).

To test longitudinal associations between physical exercise at baseline and cognitive function at follow-up, a similar approach to cross-sectional analyses was conducted with relevant covariables measured at baseline included in the regression models.

To test whether associations between physical exercise categories and cognitive domain scores differ across the age span, interactions between physical exercise and age (mean centered) and physical exercise and age (squared) were examined by adding multiplicative interaction terms to fully adjusted models in both cross-sectional and longitudinal analyses.

Two supplemental analyses were conducted. First, to examine the influence of time lag in weeks between DEGS1 and DEGS1-MH on the cross-sectional associations between physical exercise (DEGS1 measure) and cognitive domain scores (DEGS1-MH measure), time lag was included in separate models. Additionally, we included interaction terms between physical exercise and the number of weeks between examinations (mean centered and squared) in adjusted regression models.

Second, in relation to the longitudinal analysis, we assessed selection bias by examining the characteristics associated with follow-up among GNHIES98 participants with complete data in 1997-1999 who had originally consented for follow-up and who were still alive in 2008-2011 using logistic regression analysis (dependent variable: follow-up, yes/no).

Cases with missing values were deleted listwise. Statistical analyses were performed using Stata/SE 14. P-values at the 5% level and lower were considered significant.

3. Results

Characteristics of the cross-sectional sample and the longitudinal sample according to physical exercise per week are summarized in Table 1. Compared to the cross-sectional sample (DEGS1, 2008-2011), more participants in the longitudinal sample (GNHIES98, 1997-1999) reported no regular physical exercise (38.9% vs. 30.0%). In both samples, participants reporting no physical exercise: were older, had lower educational levels, and more often were currently smoking, had an intake of <3 portions of fruit and vegetables per day and were obese compared to those who regularly engaged in physical exercise.

TABLE 1

3.1 Cross-sectional associations between physical exercise and cognition

Participants engaging in no physical exercise achieved poorer test results and had lower cognitive domain scores than participants who regularly engaged in physical exercise (Figure 1 and Supplementary material Table A.2). Table 2 shows results of unadjusted and adjusted linear regression models examining cross-sectional associations of physical exercise with cognitive domain scores. Compared to no exercise, increased physical exercise was significantly associated with higher executive function scores in unadjusted (<2h: ß=0.34; ≥2h: ß=0.46, all p<0.001) and all adjusted models (fully adjusted model <2h: ß=0.12; ≥2h: ß=0.17, all p<0.001), indicating a positive dose-response relationship between the weekly cumulative duration of physical exercise and executive function. Similar, albeit slightly weaker, associations were found between physical exercise and memory scores (fully adjusted model <2h: ß=0.08, p=0.009; ≥2h: ß=0.08, p=0.026).

FIGURE 1, TABLE 2

3.2 Longitudinal associations between physical exercise and cognition

Longitudinal associations between physical exercise at baseline (GNHIES98) and cognition at follow-up (DEGS1-MH) were similar to findings in the cross-sectional analyses. Higher weekly duration of physical exercise at baseline was associated with better cognitive test results (Supplementary material Table A.3) and domain scores (Figure 1, Table 2) at follow-up. Again, slightly weaker associations were found between physical exercise and memory scores compared to executive function (fully adjusted model for executive function <2h: ß=0.14, p<0.001; ≥2h: ß=0.15, p=0.001; fully adjusted model for memory <2h: ß=0.09, p=0.036; ≥2h: 0.08, p=0.114).

3.3 Associations across the age span

In both cross-sectional and longitudinal analyses, there was no evidence of an interaction between physical exercise and age (mean centered or squared) on cognitive domain scores in adjusted models (all p-values >0.10).

3.3 Supplemental analyses

First, the influence of time lag between DEGS1 and DEGS1-MH on the cross-sectional associations was examined. The inclusion of time lag in weeks (mean centered and squared) in adjusted models did not materially change effect estimates for physical exercise and no independent effect of time lag on cognitive domain scores was found (detailed results not reported). In addition, no significant interactions (all p-values >0.10) between mean centered and squared time lag and physical exercise on cognitive function were found in adjusted models.

Second, selection bias in relation to the longitudinal analysis was assessed. In the longitudinal sample, GNHIES98 participants included in this analysis differed from those not included. According to logistic regression analyses, participants included in the longitudinal sample were significantly older, had higher levels of education, more often engaged in physical exercise, reported less current smoking, less often abstained from alcohol, and reported more fruit and vegetable consumption at baseline (see Supplementary material Table A.4 for details on measurement and results). No differences were observed for sex, obesity, or self-reported physician lifetime diagnoses of stroke, coronary heart disease and myocardial infarction.

4. Discussion

In this large, nationwide population-based study of adults aged 18 to 79 years in Germany, more weekly hours of physical exercise were significantly associated with better executive function and memory in both cross-sectional analysis and longitudinal analysis over a 12 year follow-up period. Individuals reporting more hours of physical exercise per week showed better test results in a comprehensive neuropsychological test battery providing evidence of a dose-response relationship. This positive association of physical exercise and cognitive function was robust after adjustment for relevant confounders. In addition, there was no evidence of differential effects according to age, indicating consistent associations across the adult life span.

In general, our cross-sectional results are in line with previous studies with small and non-population-based samples of young or middle-aged adults that have been summarized in a systematic review.[6] To our knowledge, our study is the first longitudinal study on the association of physical exercise and cognitive function including a continuous age range from young to older adults (i.e. 17 to 67 years at baseline). Previous longitudinal studies in this age group have found mainly positive associations between physical activity and cognitive function but differ in age range and other methodological aspects from our study.[7-9] However, previous studies have not all reported consistent results with some reporting positive associations between physical activity and cognitive function only among men[7] and another only among women.[9] Our findings are consistent with Dregan and Gulliford[8] who reported lifelong associations between leisure-time physical activity and memory and executive functioning for both sexes and a dose-response relationship in a UK birth cohort aged 11-50 years. In our study, the association of physical exercise and cognitive function seemed stronger for executive function than memory, consistent with previous research on young and middle-aged,[6,8] as well as older adults.[27]

Although the size of effects in our study was small, they indicate that higher levels of physical exercise may help to maintain higher levels of cognitive function throughout adulthood.

Although a causal link between physical exercise and cognitive function cannot be unequivocally drawn from our study, it is a possible explanation of our findings. This link is biologically plausible from evidence indicating that regular aerobic exercise leads to improvements in brain structures, such as increased capillary, blood vessel and gray and white matter density, an increased number of neurons or increased size of the hippocampus.[28,29]

With regard to healthy cognitive aging, raising physical activity levels throughout adulthood is a promising and potentially low cost public health intervention supported by some, albeit currently limited, economic evidence for this type of approach.[30] Results of a meta-analysis support our findings by showing that aerobic exercise has differential effects on different cognitive domains and has its strongest effects on executive function.[31] However, recent meta-analyses of randomized controlled trials in older cognitively healthy or impaired individuals present mixed findings of their effectiveness.[32,33] Methodological problems and the complexity of delivering effective physical activity interventions with adequate uptake, adherence, duration and intensity might explain these mixed findings.[33] Long-term effective intervention studies including healthy younger adults are lacking and high quality trials including younger age groups with long-term follow-up are needed. One example of this approach, The Finnish Geriatric Intervention Study to Prevent Cognitive Impairment and Disability (FINGER), used a 2 year multidomain intervention including exercise combined with diet, cognitive training and vascular risk monitoring and found better cognitive functioning in individuals aged 60-77 years at-risk for cognitive decline.[34] Further trails of this nature, particularly in younger age groups and with long follow-up times, would help better inform public health policy and recommendations for the types and quantity of physical activity that are required to improve or maintain cognitive function.[3]

Some limitations apply to our study. First, this study is limited because of its observational study design. There was considerable loss to follow-up for the longitudinal sample and participants and non-participants of the longitudinal sample differed, a common problem in this type of analysis (see Supplementary material Table A.4). We attempted to minimize any effects of selection bias by controlling for these differences in the fully-adjusted models. The similarity of cross-sectional and longitudinal results in our study gives us confidence that our findings are robust. Second, physical exercise measurement was based on self-report and therefore may be over and/or understated and no information was collected on the types and intensity of activities. Also, we had no information on other activities, such as work-related physical activity. Although our physical exercise measurement is commonly used in national level health surveys and has shown robust estimations over time,[20] further testing of its psychometric properties, and comparisons with other physical activity measures, are still needed. Third, although our analyses were adjusted for important confounders we were not able to control for all possible confounders, e.g. environmental factors.[35] However, in additional analyses we did further adjust our models for cardiovascular disease and risk factors and current depressive symptoms, which could be conceptualized both as potential confounders or intermediate variables in the causal chain between physical activity and cognitive function and no substantial changes to the main results were found (data not shown). In general, we found robust associations with physical exercise for executive function and slightly weaker associations for memory. Fourth, we cannot completely rule out reverse causation. Individuals with better cognitive function might be more physically active than those with lower or even impaired cognitive function. The substantial confounding effect of education in our models potentially supports this explanation (Table 2). However, the association of physical exercise and cognitive function remained significant following adjustment for level of education in our models.

5. Conclusion

In this large, nationwide population-based study of adults aged 18 to 79 years in Germany, more hours of physical exercise per week were associated with better executive function and memory in cross-sectional and longitudinal analysis with no evidence for differential effects by age. Due to the strengths of our cross-sectional and longitudinal population study design, we assume our results are generalizable regarding men and women of this age group. These findings support public health interventions to increase physical activity to preserve and potentially improve cognitive health over the lifespan. Future studies on physical activity and cognitive function should include broad age ranges and long-term follow-up to maximise understanding of effective interventions across the lifecourse.

Practical implications

- Increasing physical exercise may enhance current and future cognitive function among adult women and men.

- Raising levels of physical exercise in the population may be promising for prevention of dementia across the adult lifespan.

- Public health interventions and messages for enhancing physical exercise for this prevention aim should target all adult age groups.

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Table 1 Sample characteristics

	Cross-sectional sample (assessment years 2008-2011)				Longitudinal sample (baseline assessment years 1997-1999)			
		Physical exercise (hours per week)				Physical exercise (hours per week)		
	Total	0	<2	≥2	Total	0	<2	≥2
Characteristic	(n=3535)	(n=1061)	(n=1551)	(n=923)	(n=1624)	(n=632)	(n=637)	(n=355)
Women, n (%)	1833 (51.9)	508 (47.9)	888 (57.3)	437 (47.4)	861 (53.0)	334 (52.9)	372 (58.4)	155 (43.7)
Age (years), mean (SD)	52.5 (16.0)	55.3 (15.2)	51.9 (15.8)	50.2 (16.8)	44.8 (11.9)	46.5 (11.9)	44.3 (11.6)	42.7 (12.1)
Age group (years), n (%)								
18-39	772 (21.8)	175 (16.5)	354 (22.8)	243 (26.3)	591 (36.4)	199 (31.5)	241 (37.8)	151 (42.5)
40-59	1376 (38.9)	407 (38.4)	613 (39.5)	356 (38.6)	852 (52.5)	336 (53.2)	343 (53.9)	173 (48.7)
60+[a]	1387 (39.2)	479 (45.2)	584 (37.7)	324 (35.1)	181 (11.2)	97 (15.4)	53 (8.3)	31 (8.7)
Level of education, n (%)								
Low	1067 (30.2)	450 (42.4)	428 (27.6)	189 (20.5)	577 (35.5)	284 (44.9)	191 (30.0)	102 (28.7)
Medium	1748 (49.5)	463 (43.6)	506 (52.0)	479 (51.9)	754 (46.4)	282 (44.6)	305 (47.9)	167 (47.0)
High	720 (20.4)	148 (14.0)	317 (20.4)	255 (27.6)	293 (18.0)	66 (10.4)	141 (22.1)	86 (24.2)

Table 1 *continued*

	Cross-sectional sample (assessment years 2008-2011)				Longitudinal sample (baseline assessment years 1997-1999)			
	Physical exercise (hours per week)				Physical exercise (hours per week)			
Current smoking, n (%)	834 (23.6)	306 (28.8)	349 (22.5)	179 (19.4)	441 (27.2)	181 (28.6)	170 (26.7)	90 (25.4)
Alcohol consumption (g/d), n (%)								
0	384 (10.9)	149 (14.0)	172 (11.1)	63 (6.8)	217 (13.4)	119 (18.8)	64 (10.1)	34 (9.6)
≤10/20 women/men	2492 (70.5)	708 (66.7)	1104 (71.2)	680 (73.7)	1058 (65.2)	390 (61.7)	423 (66.4)	245 (69.0)
>10/20 women/men	659 (18.6)	204 (19.2)	275 (17.7)	180 (19.5)	349 (21.5)	123 (19.5)	150 (23.6)	76 (21.4)
<3 portions of fruit and vegetables per day, n (%)	2301 (65.1)	788 (74.3)	1006 (64.9)	507 (54.9)	858 (52.8)	370 (58.5)	316 (49.6)	172 (48.5)
Obesity (BMI>=30kg/m²), n (%)	867 (24.5)	339 (32.0)	402 (25.9)	126 (13.7)	305 (18.8)	169 (26.7)	110 (17.3)	26 (7.3)

Not all percentages add to 100 due to rounding error.

[a]Cross-sectional sample: 60-79 years; Longitudinal sample: 60-67 years.

BMI, body mass index.

Table 2 Cross-sectional and longitudinal associations between physical exercise and cognition in linear regression models

	Cross-sectional associations (DEGS1-MH; n=3535)					Longitudinal associations (GNHIES98-baseline, DEGS1-MH-follow-up; n=1624)				
Cognitive domain scores	Physical exercise: No exercise [reference]					Physical exercise: No exercise [reference]				
	<2 hours per week		≥2 hours per week			<2 hours per week		≥2 hours per week		
	ß coeff. (95% CI)	p	ß coeff. (95% CI)	p	p_{trend}	ß coeff. (95% CI)	p	ß coeff. (95% CI)	p	p_{trend}
Executive function										
Model 1	0.34 (0.27, 0.41)	<0.001	0.46 (0.39, 0.54)	<0.001	<0.001	0.35 (0.25, 0.44)	<0.001	0.39 (0.28, 0.50)	<0.001	<0.001
Model 2	0.20 (0.15, 0.25)	<0.001	0.30 (0.25, 0.36)	<0.001	<0.001	0.22 (0.15, 0.30)	<0.001	0.25 (0.16, 0.34)	<0.001	<0.001
Model 3	0.14 (0.09, 0.19)	<0.001	0.20 (0.15, 0.26)	<0.001	<0.001	0.16 (0.09, 0.23)	<0.001	0.18 (0.09, 0.27)	<0.001	<0.001
Model 4	0.12 (0.07, 0.17)	<0.001	0.17 (0.11, 0.23)	<0.001	<0.001	0.14 (0.07, 0.21)	<0.001	0.15 (0.06, 0.24)	0.001	<0.001
Memory										
Model 1	0.27 (0.20, 0.34)	<0.001	0.32 (0.24, 0.40)	<0.001	<0.001	0.28 (0.18, 0.38)	<0.001	0.26 (0.15, 0.38)	<0.001	<0.001
Model 2	0.14 (0.08, 0.20)	<0.001	0.20 (0.13, 0.26)	<0.001	<0.001	0.17 (0.08, 0.26)	<0.001	0.18 (0.07, 0.28)	0.001	<0.001
Model 3	0.09 (0.03, 0.15)	0.003	0.11 (0.04, 0.18)	0.001	0.001	0.11 (0.03, 0.20)	0.011	0.12 (0.01, 0.22)	0.027	0.014
Model 4	0.08 (0.02, 0.14)	0.009	0.08 (0.01, 0.15)	0.026	0.021	0.09 (0.01, 0.18)	0.036	0.08 (-0.02, 0.19)	0.114	0.071

Model 1=unadjusted.

Model 2= adjusted for age (mean centered), age (squared) and sex.

Model 3=Model 2 additionally adjusted for level of education.

Model 4=Model 3 additionally adjusted for current smoking, alcohol consumption, fruit and vegetables consumption and obesity.

DEGS1-MH, mental health module of the German Health Interview and Examination Survey for Adults.

GNHIES98, German National Health Interview and Examination Survey 1998; DEGS1-MH, mental health module of the German Health Interview and Examination Survey for Adults.

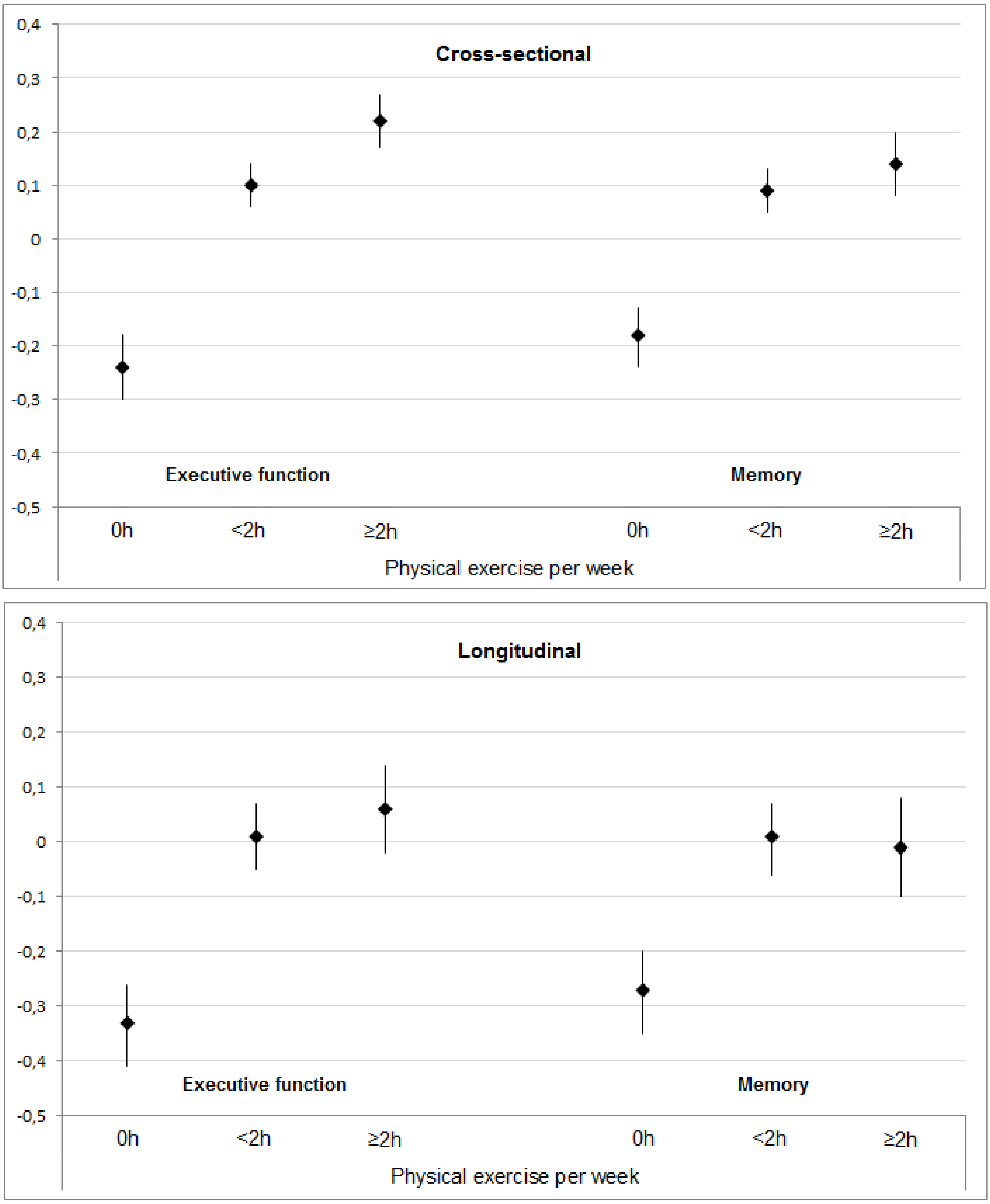

Figure 1. Means and 95% confidence intervals of cognitive domain scores (z-scores) according to physical exercise in hours (h) per week

Supplementary material

Gaertner B, Buttery AK, Finger JD, Wolfsgruber S, Wagner M & Busch MA. Physical exercise and cognitive function across the life span: results of a nationwide population-based study.

Supplementary material Table A.1. Description of neuropsychological tests

Supplementary material Table A.2. Cross-sectional analysis: Cognitive scores by physical exercise in DEGS1-MH (n=3535)

Supplementary material Table A.3. Longitudinal analysis: Cognitive scores at follow-up (DEGS1-MH) by physical exercise at baseline (GNHIES98) (n=1624)

Supplementary material Table A.4. Logistic regression analyses examining characteristics associated with follow-up in the longitudinal sample

Supplementary material Table A.1 Description of neuropsychological tests

Domain of cognitive functioning	Neuropsychological test	Short description
Executive function		
verbal working memory	digit span backward test (DSBT) from the Wechsler Intelligence Scale for Adults[1]	measuring the number of digit sequences of increasing length (2-8 digits) that were correctly recalled in reverse order (range 0-14)
executive function and mental speed	trail making tests (TMT-A, TMT-B)[2]	measuring the time in seconds needed to correctly and accurately connect an ordered sequence of 25 consecutive targets (numbers in TMT-A and alternating numbers and letters in TMT-B)
executive function and mental speed	letter digit substitution test (LDST)[3]	measuring the number of digits correctly substituted within 60 seconds (range 0-125)
executive function and mental speed	verbal fluency test (VFT) from CERAD[4,5]	measuring the number of animals named within 60 seconds
Memory	immediate and delayed recall from the German language version of CERAD[4,5]	Trial 1-3 (immediate recall) and Trial 4 (delayed recall) of a 10-word lists measuring the number of correctly recalled words (range 0-10) per trial

CERAD, The Consortium to Establish a Registry for Alzheimer’s Disease.

Supplementary material Table A.2 Cross-sectional analysis: Cognitive scores by physical exercise in DEGS1-MH (n=3535)

Cognitive scores	N	Total (n=3535) mean (95% CI)	Physical exercise: 0 hours per week (n=1061) mean (95% CI)	<2 hours per week (n=1551) mean (95% CI)	≥2 hours per week (n=923) mean (95% CI)
Cognitive test scores[a]					
DSBT	3531	6.2 (6.1,6.2)	5.8 (5.7, 5.9)	6.2 (6.1, 6.3)	6.5 (6.4, 6.6)
TMT-A	3528	34.6 (34.1, 35.1)	38.4 (37.2, 39.5)	33.4 (32.7, 34.1)	32.2 (31.4, 33.1)
TMT-B	3497	83.2 (82.2, 85.0)	93.4 (90.6, 96.3)	81.1 (79.1, 83.2)	74.9 (72.6, 77.1)
LDST	3509	32.1 (31.9, 32.4)	30.2 (29.7, 30.6)	32.7 (32.3, 33.1)	33.5 (33.0, 34.0)
VFT	3527	25.9 (25.7, 26.2)	24.6 (24.2, 25.0)	26.3 (25.9, 26.6)	26.9 (26.5, 27.3)
Word list - Immediate recall 1	3535	5.9 (5.8, 5.9)	5.6 (5.5, 5.6)	6.0 (5.9, 6.0)	6.1 (6.0, 6.1)
Word list - Immediate recall 2	3535	7.5 (7.4, 7.5)	7.2 (7.1, 7.3)	7.6 (7.5, 7.7)	7.6 (7.5, 7.7)
Word list - Immediate recall 3	3535	8.4 (8.3, 8.4)	8.2 (8.1, 8.3)	8.5 (8.4, 8.6)	8.5 (8.4, 8.6)
Word list - Delayed recall	3533	7.3 (7.2, 7.4)	7.0 (6.9, 7.1)	7.4 (7.3, 7.5)	7.5 (7.4, 7.6)
Cognitive domain scores[b]					
Executive function	3535	0.03 (-0.01, 0.06)	-0.24 (-0.30, -0.18)	0.10 (0.06, 0.14)	0.22 (0.17, 0.27)

Memory	3535	0.02 (-0.01, 0.05)	-0.18 (-0.24, -0.13)	0.09 (0.05, 0.13)	0.14 (0.08, 0.20)

[a]For the TMT-A and TMT-B lower test scores represent higher cognitive function. For all other cognitive tests, higher values represent better cognitive function.

[b]Presented values are weighted latent factor scores derived from confirmatory factor analysis based on z-standardized individual test scores; executive function scores ranged from -4.53 to 2.24, memory scores ranged from -3.88 to 1.81, with higher values indicating better cognitive function.

DEGS1-MH, mental health module of the German Health Interview and Examination Survey for Adults; DSBT, digit span backward test; TMT-A, trail making test-A; TMT-B, trail making test-B; LDST, letter digit substitution test; VFT= verbal fluency test.

Supplementary material Table A.3 Longitudinal analysis: Cognitive scores at follow-up (DEGS1-MH) by physical exercise at baseline (GNHIES98) (n=1624)

			Physical exercise		
		Total (n=1624)	0 hours per week (n=632)	<2 hours per week (n=637)	≥2 hours per week (n=355)
Cognitive scores	N	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)
Raw scores of individual test[a]					
DSBT	1622	6.0 (5.9, 6.1)	5.7 (5.6, 5.9)	6.0 (5.9, 6.2)	6.3 (6.1, 6.5)
TMT-A	1620	36.4 (35.6, 37.2)	38.8 (37.3, 40.2)	35.0 (33.9, 36.0)	34.7 (33.1, 36.3)
TMT-B	1604	88.6 (86.5, 90.7)	98.2 (94.4, 102.0)	83.9 (80.9, 86.8)	80.0 (76.3, 83.7)
LDST	1606	31.0 (30.6, 31.3)	29.3 (28.7, 29.9)	31.9 (31.3, 32.5)	32.1 (31.4, 32.8)
VFT	1617	25.8 (25.5, 26.1)	24.8 (24.2, 25.3)	26.3 (25.8, 26.8)	26.8 (26.1, 27.5)
Word list – Immediate recall 1	1624	5.7 (5.6, 5.7)	5.4 (5.3, 5.6)	5.8 (5.7, 5.9)	5.8 (5.7, 6.0)
Word list – Immediate recall 2	1624	7.4 (7.3, 7.4)	7.1 (7.0, 7.3)	7.5 (7.4, 7.6)	7.4 (7.3, 7.6)
Word list – Immediate recall 3	1624	8.3 (8.2, 8.4)	8.1 (8.0, 8.2)	8.5 (8.4, 8.6)	8.4 (8.3, 8.5)
Word list – Delayed recall	1622	7.0 (6.9, 7.1)	6.8 (6.6, 6.9)	7.2 (7.0, 7.3)	7.2 (7.0, 7.4)
Cognitive domain scores[b]					
Executive function	1624	-0.11 (-0.16, -0.07)	-0.33 (-0.41, -0.26)	0.01 (-0.05, 0.07)	0.06 (-0.02, 0.14)
Memory	1624	-0.11 (-0.15, -0.06)	-0.27 (-0.35, -0.20)	0.01 (-0.06, 0.07)	-0.01 (-0.10, 0.08)

[a]For the TMT-A and TMT-B lower test scores represent higher cognitive function. For all other cognitive tests, higher values represent better cognitive function.

[b]Presented values are weighted latent factor scores derived from confirmatory factor analysis based on z-standardized individual test scores; executive function scores ranged from -4.53 to 1.95, memory scores ranged from -4.72 to 1.80, with higher values indicating better cognitive function.

DEGS1-MH, mental health module of the German Health Interview and Examination Survey for Adults; GNHIES98, German National Health Interview and Examination Survey 1998; DSBT, digit span backward test; TMT-A, trail making test-A; TMT-B, trail making test-B; LDST, letter digit substitution test; VFT, verbal fluency test.

Supplementary material Table A.4 Logistic regression analyses examining characteristics associated with follow-up in the longitudinal sample[a]

		Follow-up examination		Logistic regression			
		No (n=4505)	Yes (n=1624)	Unadjusted (n=6129)		Adjusted for all other variables (n=6110)	
	N	n (%)/ mean (SD)	n (%)/ mean (SD)	OR (95% CI)	p	OR (95% CI)	p
Sex	6129						
Men		2164 (48.0)	763 (47.0)	[Reference]		[Reference]	
Women		2341 (52.0)	561 (53.0)	1.04 (0.93, 1.17)	0.467	1.08 (0.95, 1.22)	0.222
Age (years)	6129	43.3 (16.0)	44.8 (11.9)	1.01 (1.01, 1.01)	<0.001	1.01 (1.01, 1.01)	<0.001
Level of education	6129						
Low		1998 (44.4)	577 (35.5)	[Reference]		[Reference]	
Medium		1929 (42.8)	754 (46.4)	1.35 (1.19, 1.53)	<0.001	1.42 (1.24, 1.63)	<0.001
High		578 (12.8)	293 (18.0)	1.76 (1.48, 2.08)	<0.001	1.57 (1.32, 1.88)	<0.001
Physical exercise (hours per week)	6129						
0		2102 (46.7)	632 (38.9)	[Reference]		[Reference]	
<2		1566 (34.8)	637 (39.2)	1.35 (1.19, 1.54)	<0.001	1.25 (1.09, 1.43)	0.001

≥2		837 (18.6)	355 (21.9)	1.41 (1.21, 1.64)	<0.001	1.34 (1.14, 1.58)	<0.001
Current smoking	6129						
Yes		1611 (35.8)	441 (27.2)	[Reference]		[Reference]	
No		2894 (64.2)	1183 (72.8)	1.49 (1.32, 1.69)	<0.001	1.37 (1.20, 1.56)	<0.001
Alcohol consumption (g/d)	6129						
0		848 (18.8)	217 (13.4)	0.68 (0.58-0.80)	<0.001	0.72 (0.31-0.85)	<0.001
≤10/20 women/men		2820 (62.6)	1058 (65.2)	[Reference]		[Reference]	
>10/20 women/men		837 (18.6)	349 (21.5)	1.11 (0.96, 1.28)	0.149	1.11 (0.96, 1.29)	0.171
<3 portions of fruit and vegetables per day	6129						
Yes		2594 (57.6)	858 (52.8)	[Reference]		[Reference]	
No		1911 (42.4)	766 (47.2)	1.21 (1.08, 1.36)	0.001	1.10 (0.98, 1.24)	0.102
Obesity (BMI>=30kg/m^2)	6129						
Yes		917 (20.4)	305 (18.8)	[Reference]		[Reference]	
No		3588 (79.6)	1319 (81.2)	1.11 (0.96, 1.28)	0.173	1.05 (0.90, 1.22)	0.508
Stroke[b]	6110						
Yes		39 (0.9)	12 (0.7)	[Reference]		[Reference]	

No		4452 (99.1)	1607 (99.3)	1.17 (0.61, 2.24)	0.630	1.17 (0.60, 2.28)	0.637
Coronary heart disease[b]	6110						
Yes		189 (4.2)	53 (3.3)	[Reference]		[Reference]	
No		4302 (95.8)	1566 (96.7)	1.30 (0.95, 1.77)	0.099	1.40 (0.99, 1.99)	0.061
Myocardial infarction[b]	6110						
Yes		64 (1.4)	16 (1.0)	[Reference]		[Reference]	
No		4427 (98.6)	1603 (99.0)	1.44 (0.83, 2.51)	0.187	1.20 (0.65, 2.21)	0.551

[a]Limited to those who had originally provided consent for follow-up and who were still alive in 2008-2011.

[b]Self-reported chronic diseases ("Has a doctor ever diagnosed you as having..?") at GNHIES98. Not all percentages add to 100 due to rounding error.

GNHIES98, German National Health Interview and Examination Survey 1998; OR, odds ratio; BMI, body mass index.

Supplementary material A-References

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